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On

INSECTILE AND VERMTFORM EXPLORATORY ROBOTS

I

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Inventor(s):

Sarita Thakoor
Brett Kennedy
Anilkumar P Thakoor

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JPL Technology Reporting Office

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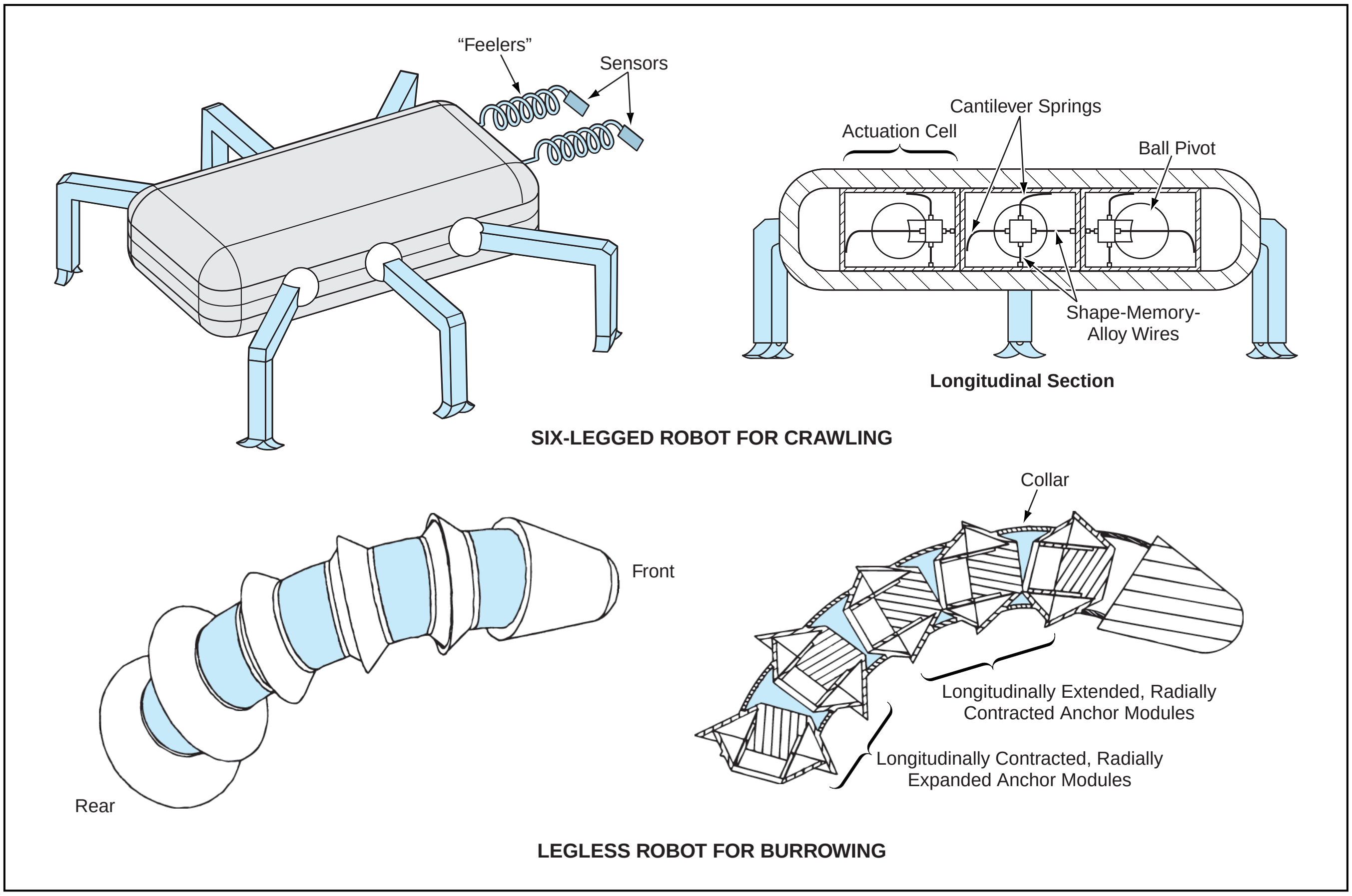
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

November 99

Insectile and Vermiform Exploratory Robots

These robots would carry sensors in hazardous environments.

NASA's Jet Propulsion Laboratory, Pasadena, California



Robots That Look and Move Like Small Animals would be developed for use in a variety of exploratory tasks. Six-legged robots could be developed into a mass-producible, mass-deployable units to search for antipersonnel mines. Legless robots similar to the one depicted here could burrow in earthquake rubble to search for survivors.

A six-legged robot resembling an insect and a legless segmented robot resembling a worm (see figure) have been proposed as prototypes of biomorphic explorers — small, mobile, exploratory robots that would be equipped with microsensors and would feature animallike adaptability and mobility. Biomorphic explorers and related concepts have been described in several previous articles in *NASA Tech Briefs*, the most relevant being "Biomorphic Explorers" (NPO-20142), Vol. 22, No. 9, (September 1998), page 71 and "Earthwormlike Exploratory Robots" (NPO-20266), Vol. 22, No. 6, (June 1998), page 11b.

Depending on the specific environment to be explored, a biomorphic explorer might be designed to crawl, hop, slither, burrow, swim, or fly. Biomorphic explorers could be used for such diverse purposes as scientific exploration of volcanoes, law-enforcement surveillance, or microsurgery. Another potential use for biomorphic explorers is detection of antipersonnel mines; there is a pressing need for robots that could be deployed in large numbers to detect antipersonnel mines left on and in the ground after armed conflicts. The proposed six-legged robot would be designed with a view toward that application. There is also a need for burrowing robots that could search earthquake rubble for survivors; the proposed vermiform robot would be suitable for this purpose.

The proposed six-legged robot would be capable of traversing various types of terrain. The legs would be attached to a main body at shoulder ball pivots. Rotations at the shoulders would result in translations of the feet. The legs would feature telescoping segments that could be lengthened or shortened to suit the direction of motion and the terrain. For example, the legs could be shortened to obtain greater mechanical advantage for climbing, or lengthened to increase speed in level or downhill travel over smooth terrain. The legs would be tipped with footpads that could be configured to suit the terrain. For example, a scissorlike arrangement of footpad members would be use on hard terrain (e.g., rocks), while the footpad members would be spread out to form a larger contact area on soft terrain (e.g., sand). The legs and footpads would be actuated by springs paired with shape-memory-alloy (SMA) wires; within each actuator, the spring would pull or push in one direction, while the SMA wire would pull in the opposite direction by an amount that would be changed momentarily by passing a momentary electric current through the wire to heat it momentarily above its shape-memory transition temperature.

The proposed vermiform robot would be capable of both anchored rectilinear motion similar to peristalsis and a transverse motion, based on the motions of *Amphisbaenia* — a legless order of reptiles that burrow with notable efficiency. The anchored rectilinear motion would be effected by anchor modules that would look like cones paired base to base. Within each anchor module there would be a pistonlike assembly actuated by pairs of springs and SMA wires. The assembly could be actuated to either (1) shorten the module longitudinally and expand the outer cone radially to anchor in the wall of the burrow or (2) lengthen the module longitudinally and retract the outer cone from contact with the tunnel wall. For example, suppose that all anchor modules were initially in the minimum-diameter, maximum-longitudinal-length configuration. The foremost module could be expanded radially to anchor the head end, then the next module could be expanded, and so forth, in sequence from front to rear. The longitudinal shortening accompanying the radial expansion of each module would draw the trailing modules forward.

The anchor modules would be connected by collars of a flexible material in which SMA wires would be embedded at multiple circumferential positions. The SMA wires would be oriented longitudinally. The wires could be energized selectively to bend the collar; in this way, part or all of the robot body could be arched.

In both robots, artificial neural networks would receive inputs from sensors and would respond by issuing commands for the SMA actuators to effect complex combinations of motions to achieve the overall lifelike mobility. Artificial neural networks were chosen for this application because they appear to offer the maximum potential for achieving a desired combination of capability for learning, adaptability, fault tolerance, composability (ability to smoothly integrate various primitive motions into complex motions and other activities), and generality to enable application to future biomorphic explorers.

This work was done by Sarita Thakoor, Brett Kennedy, and Anil Thakoor of Caltech for **NASA's Jet Propulsion Laboratory**. *NPO-20381*

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NTR Inventor's Report

NASA CASE NO.
JPL CASE NO.

Biomorphic Multi-Terrain Robots to Explore Earth or Outer Planets: Implementation Designs

Sarita Thakoor, Brett Kennedy and Anil Thakoor

1. Novelty:

Our approach is directed towards obtaining: a new capability and significant potential advantages, especially when traversing unusual and difficult terrain (such as loose granular surface. soft flour like soil. icy surface, or subsurface ocean) bv imitating the mobilitv attributes of animals. Mimicking biology, such "bio-morphic explorers" will possess varied mobility modes (with ease of reconfigurability from one form to another, utilizing common building blocks) surface-roving, burrowing, hopping, hovering, or flying, to accomplish surface, subsurface, and atmospheric exploration. They would combine the functions of advanced mobility and sensing with a choice of electronic and/or photonic control. Preprogrammed for a specific function, they could serve as "no-uplink, one-way communicating" beacons, spread over the exploration site, autonomously looking for/at the object of interest. The biomorphic controls promise an excellent approach to capture learning and adaptivity in the behavipr of the actuator(s) assembly to autonomously match with the changing ambient/terrain conditions. This innovation implements a new paradigm in mobility combining novel "bio-morphic" control strategies and advanced flexible actuators. Two specific implementation designs are highlighted and implementation of neural control is discussed in this report.

2. Technical Disclosure

A. Problem and

B. Solution

Conventional control techniques do not allow adapting to situations and ease of reconfiguration to a changing suite of terrain/mobility requirements. This innovation, combining biomorphic controls and direct driven advanced flexible actuators offers, for the first time, a new direction in ***advanced mobility with new capabilities*** of adapting to terrain, enhanced spatial access owing to flexibility, scalability, and ease of multiplicity due to batch fabrication of common constituent building blocks. There is a pressing need[37,44] for new methods to detect mine fields, locate and identify every single mine, particularly small plastic APMs, and clean-up the sites. APMs may be as small as a pack of cigarettes and weigh less than 50 g. Bio-morphic explorers: low cost, scalable tetherless mobile robots, small in size (- 5cms) and tailored for APM sensing,. would enable a viable solution particularly against such anti-personnel mines. Navy and geologic survey respectively have need for such explorers for under-water and hazardous volcanic or earthquake area exploration.

C. Detailed Report attached

Biomorphic Multi-Terrain Robots to Explore Earth or Outer Planets: Implementation Designs

I Innovative Claims

The Jet Propulsion Laboratory (JPL) will develop enabling robotic technology for "bio-morphic explorers" consisting of a unique combination of direct-driven, flexible actuators and their adaptive control by fault-tolerant biomorphic *algorithms.* Advanced composite materials/flexible substrate-based flexible actuators, employing innovative mechanisms would provide the desired combination of *high force and displacement characteristics,* to form the flexible active appendages of the explorer. Powerful biomorphic ***controls*** combining neural and evolutionary genetic algorithms can achieve learning and adaptation in the actuators to autonomously match with the changing ambient/terrain conditions. Combining the flexible actuators and biomorphic controls would offer therefore for the first time a new direction in ***advanced mobility with new capabilities*** of adapting to terrains, enhanced spatial access owing to flexibility, scalability, and ease of multiplicity due to batch fabrication. These new capabilities offer a high payoff as a new paradigm (Figure 1) for surveillance, advanced warning systems and clean-up robot crew in hazardous areas. Robots highly adapted to variety of environments, available in multitudes, at low cost, will be enabled. Applications include environmental clean-up, security and intelligence data acquisition, and hazardous area exploration for Industrial/DOD needs etc.

In this effort we select truly simple but reconfigurable actuation mechanisms to interface with the adaptive neural controls and will demonstrate the ability to adapt mobility within realistic terrain conditions varying from granular sandy terrain to rocky terrain. Leveraging from the controls hardware and software expertise at JPL, we will demonstrate in this three year effort a biomorphic explorer with its adaptive mobility and reconfigurability attributes by control algorithms implemented in artificial neural network chip hardware. Three demonstrations, one at the end of each year have been carefully designed to manage the risk. The first year will address the high risk items to demonstrate feasibility, followed by a focussed two year effort to demonstrate a functional biomorphic explorer.

Made from common building block mobility modules such bio-morphic explorers may possess varied mobility modes (surface-roving, burrowing, hopping, hovering, or flying) to accomplish surface, subsurface, and atmospheric exploration. They would combine the functions of advanced mobility and sensing with a choice of electronic and/or photonic control. Preprogrammed for a specific function, they could serve as "no-uplink, one-way communicating" beacons, spread over the exploration site, autonomously looking *for/at the object* of *interest*. In a hierarchical organization, these biomorphic explorers would allow a wide-spread and affordable site exploration with a substantial amount of

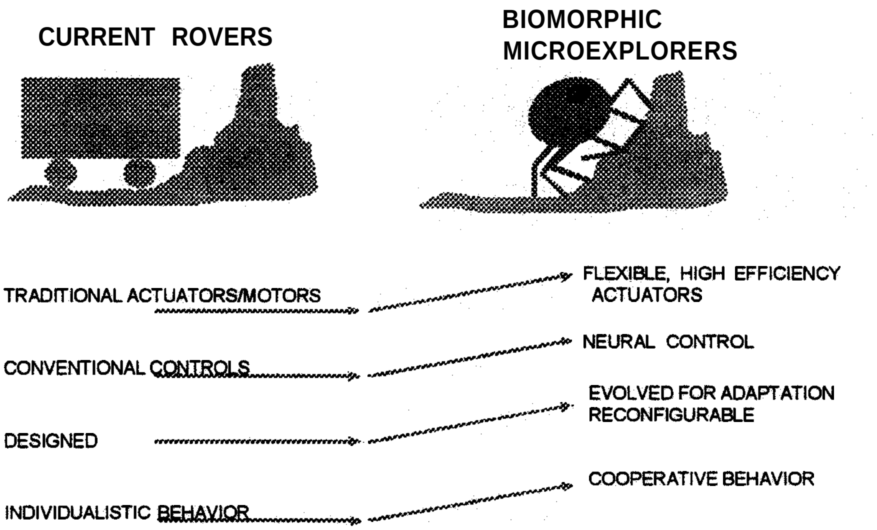


Figure 1: Mobility: Paradigm Shift

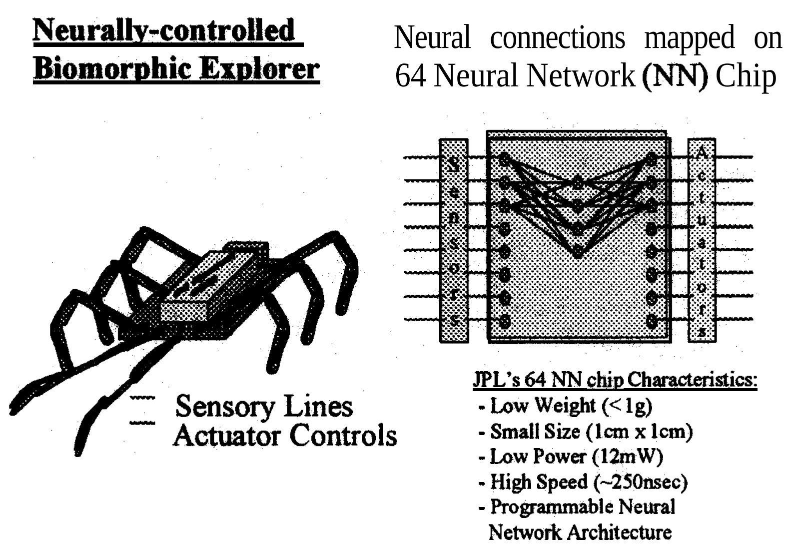


Figure 2: Biomorphic Explorer Controlled by a Neurat chip

scouting for information about a new or hazardous area at lower cost and risk. Combining a fast running rover to cover long distances with numerous small bio-morphic explorers for sensing and locating anti-personnel mines (APMs) for example is one scenario. There is a pressing need[37,44] for new methods to detect mine fields, locate and identify every single mine, particularly small plastic APMs, and clean-up the sites. APMs may be as small as a pack of cigarettes and weigh less than 50 g. Bio-morphic explorers: low cost, scalable tetherless mobile robots, small in size **(~ 5cms)** and tailored for APM sensing, would enable a viable solution particularly against such anti-personnel mines. Navy and geologic survey respectively have need for such explorers for under-water and hazardous volcanic or earthquake area exploration.

*Key New Features of "**Biomorphic Explorers**"*

AI. Advanced flexible actuators will allow the design of direct-driven limbs (legs/muscles/appendages) bypassing the need for complex chassis (motors and drive systems). The limbs will possess the added advantage of reconfigurability. The mobility module has following new features:

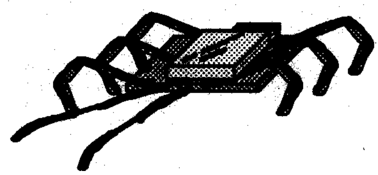
i. Reconfigurable leg/body adaptable to terrain conditions by shape reconfiguration as well as gait change/control
ii. Obstacle avoidance
III. Foldable sensor deployment mechanism ("feeler")
iv. Active, sensor-based configuration/gait control

A2. Biologically inspired controls (based on artificial neural **networks**[9,12,13](ANN) **implemented** in low-power VLSI hardware as shown in figure 2 with their characteristics highlighted) called 'biomorphic' in this document would be especially suited for controlling the inherently non-linear flexible actuators.

A3. Revolutionary mechanisms for adaptation would supercede traditional inflexible designs. For example, sensor-triggered control sequence to the legs may be determined for optimal ways to move in different environmental conditions.

A4 Ultimately, cooperative behavior among many such explorers would enable new types of missions. Using groups of small, ihexpensive bio-morphic explorers in conjunction with larger, traditional mobile robots will enable tasks which are too complex for a single robot.

Table 1: Key Specifications of the Biomorphic Explorer to be demonstrated

Physical Embodiment	
Technology Used	Shape memory alloy wires, Piezoceramic wafers
Mass (grams)	50
Volume (cc)	100
Communication Range (Meters)	15-100
Power reqd. (mW)	1000

II. Technical Approach:

Realization of the vision of small, expendable, bio-morphic explorers requires four key components: (1) microsensors, (2) micropower, (3) advanced mobility and (4) microcommunication devices. The development of three out of these four essential components (except the advanced mobility) is already driven by multi-billion dollar commercial market forces. For example, microsensors such as microimagers are already being miniaturized to serve the voracious appetite of digital imaging for surveillance, security, science, and entertainment. Solid state batteries with high power density are advancing at a rapid pace driven by the developments in cellular phones, handheld computers, long life watches, and other electronic gadgets. Low-power, limited range, low-bandwidth communication, adequate for the explorers, has also been addressed (e.g., Micron Communications, NEC) rather aggressively in recent years, to target the mass market of product. ID tags and inventory control. Depending on the sensor function desired and expected ambient conditions, a bio-morphic explorer could range from -1 cc in volume (weighing only a few grams, a small artificial insect), up to several hundred cc in volume (approaching a kilogram mass). For such an explorer, however, the component that has not received adequate attention from the commercial market forces is the advanced mobility. The proposed effort, therefore, focuses on the development of advanced mobility, adaptively controlled by biologically-inspired control algorithms.

This technology development and demonstration effort will result in:

(a) One (or more), fully operational, *self-contained*, autonomous, direct-driven, flexible, multi-legged, small explorer(s) ~ 5 cm in length, less than 100 gms in mass
(b) With sensor-triggered, advanced mobility attributes and reconfigurability, to capture terrain'adaptation,
(c) Controlled by the novel biomorphic algorithm(s), implemented in an on-board, low-power, VLSI ANN hardware.

The following is the three year approach to this effort:

Year 1 : A feasibility demonstration of mobility module building block in H/W under the programmed ANN chip control..
Development of basic mobility units(each comprising of two or more "legs" for the insect or an individual segment of the earthworm robot) and their mobility/configuration control mechanisms will consist of the following steps:

1. Build proof-of-concept models of **reconfigurable/flexible** key actuator mechanisms using flexible actuators to study the performance capabilities in light of known requirements, for example the application of APM localization and clean-up.
2. Develop and optimize a bio-morphic control algorithm for the control of the selected reconfigurable **design(/s)** and test performance of the selected algorithm.
3. Design the chip controller along with drivers as needed per actuator drive requirements. Adapt the programmable, reconfigurable NN64 neural net building block chip to the problem at hand based on the sensor to actuator controller connection architecture.
4. Finally, integrate the foldable mobility modules with the ANN chip-based controller, leading to the feasibility demonstration of the individual mobility module(s) in H/W under the programmed ANN chip control.

Year 2 : A demonstration of the complete explorer test structure in hardware with adaptive mobility and reconfigurability attributes under the control of the selected algorithms, implemented in software and tethered to a power source.
Fabrication and assembly of the biomorphic explorers and demonstration of their advanced, adaptive mobility and terrain-dependent reconfigurability features under the control of the optimized algorithms, implemented first in software during this phase will involve the following steps:

1. Results of year 1 will lead to mechanical design of multi-limb explorer.
2. Optimization of the selected sensors and their placement in the explorer design.
3. Fabrication and assembly of the explorer structures.

4. Interfacing of the structures with the selected optimized algorithms, implemented in software for assessment of their effectiveness.

Year 3: A final demonstration of a complete untethered explorer implemented in hardware, with its adaptive mobility and reconfigurability attributes under the control of the selected algorithms, implemented in ANN chip hardware.

1. Based on the results of year 2, modify the design of the explorer.
(a) Determine the optimized distribution of sensors
(b) Develop and implement a strategy for sensor triggered gait control, speed control, reconfigurability control for terrain adaptability, etc.
2. Refine hardware and software interface for the ANN chip for control of the explorer structure.
3. Download the algorithm generated transformation matrix as synaptic weights in the ANN chip, programmed for the control.
4. Demonstration of the biomorphic explorer and its terrain adaptibility features.

In addition to the key milestones outlined for each year above, JPL will also:

(a) Develop scenarios for location of mines and their clean-up.
(b) Assess the capabilities of different kinds of bio-morphic explorer architectures (or their suitable combinations).
(c) Conceptualize new cooperative algorithms such as groups of sensing explorers and detonating explorers working together to achieve the clean up of hazardous objects such as APM's.

A straw-man system design of the entire explorer, including a radio data (communication) link generated in this sub-task for the selected application (e.g. a mine detecting explorer) is important. It will provide a better focus on the new features appropriate for the application, and their design/performance optimization during the course of this effort.

IIIC. DETAILED TECHNICAL RATIONALE:

IIIC.1. Why Bio-morphic Explorers?

Realization of the vision of small, expendable, bio-morphic explorers requires four key components: (1) microsensors, (2) micropower, (3) advanced mobility and (4) microcommunication devices. The development of three, out of these four essential components (except the advanced mobility) is already driven by multi-billion dollar commercial market forces. For example microsensors such as microimagers are already being miniaturized to serve the voracious appetite of digital imaging business for surveillance, security, science, and entertainment.

Solid state batteries with high power density are advancing at a rapid pace driven by the developments in cellular phones, handheld computers, long life watches, and other electronic gadgets. Low-power, limited range, low-bandwidth communication, adequate for the explorers, has also been addressed (for eg Micron Communications, NEC) rather aggressively in recent years, to target the mass market of product ID tags and inventory control. Depending on the sensor function desired and expected ambient conditions, a bio-morphic explorer could range from -1 cc in volume (weighing only a few grams, a small artificial insect), up to several hundred cc in volume (approaching a kilogram mass). Based on the current technologies, Table 2 presents rough order-of-magnitude estimates

Table 2 : Rough Order-of-Man&de Estimates of Power, Mass, and Volume for a Bio-morphic Explorer

Rough Estimates	**Sensor**[18]	**Communication**[19]	Computing	**Mobility**[22]
Function Performed	Temperature, Chemical, Surface Hardness, Moisture etc.	Periodic Beacon and/or "Eureka" signal when goal accomplished **Range** -15 to **100m**	Sensor Control, **Signal** Conditioning, Motion/Articulation Control, Communication Control	Locomotion (-1 **cm/sec)**, Limb Articulation, Adaptive Shape Reconfiguration
Power Required	-100 microwatt	-10-100 milliwatt	-10-100 milliwatt	-250-500 milliwatt

of power required, mass, and volume/size, for a sensor, communication system, on-board computing, and mobility for a ~ 50 gm mass bio-morphic explorer, which would operate with a peak consumption of -1 watt power. The unpackaged mass and volume of each chip is considered in the above table. For such an explorer, however, the component that has not received adequate attention from the commercial market forces is the advanced mobility. The proposed effort therefore focuses on the development of advanced mobility, adaptively controlled by biologically-inspired control algorithms.

IIIC.2. Why Flexible Actuators ?

A limitation of current wheeled/jointed-legged mobility mechanisms is that only certain terrains that they are designed for can be accessed. Complex drive mechanisms for "transmission" of motion make them more vulnerable to failure possibilities. Also, in order to miniaturize and make many in a scalable manufacturing technique, mechanisms other than wheels are required as is pointed out with respect to the scaling issue by **LaBerbara**[31] and **Gould**[27]. Wheels, even with the most innovative suspension mechanisms, can negotiate obstacles with height at most **twice** the wheel diameter. Alternate mechanisms of mobility become quite necessary, especially as the size of the mobile system is reduced. Flexible actuators based on active mobile appendages would be direct driven, and have higher efficiency, with substantially lesser mechanical vulnerability. Most of all, these flexible actuators are adaptable to advanced forms currently in development that can be fabricated using VLSI compatible techniques that make them batch processable and scalable all the way from tens of centimeters down to submicron dimensions.

Selection/optimization of Advanced Flexible Actuators :

A survey[49] of emerging/advanced actuation technologies by S. Thakoor is summarized in Table 3. This comparison is being constantly updated, since the field of actuators is continually advancing. **Selection/optimization of smart actuator material(s)** from the rapidly advancing knowledge-base of advanced composite materials and innovative amplification techniques with interesting/useful properties (e.g. combination of high force and displacement at low power), will lead to hardware-implementable designs for the bio-morphic explorer. Table 3 presents a comparison of the different actuation technologies

Table 3: Comparison of Actuation Technologies

			POLYMERIC MATERIALS		
	PIEZOCERAMIC	SHAPE MEMORY ALLOY	PVDF and PVDF copolymers	Polynddes PMMA Polyurethanes	MAGNETO-STRICTIVE
MECHANISM	PIEZOELECTRIC & ELECTROSTRICTIVE	THERMAL: MARTENSITIC → AUSTENITIC PHASE CHANGE	PIEZOELECTRIC, PHASE TRANSITION	ELECTRO-STRICTIVE	MAGNETIC FIELD INDUCED BY COIL
STRAIN	10^{-4} TO $0.3X10^{-2}$ **	10^{-5} TO 10^{-1}	10^{-4} TO $10^{[illegible]}$	$10^{[illegible]}$ TO 10^{-1}	10^{-6} TO 10^{-2}
DISPLACEMENT	LOW TO HIGH*	MEDIUM TO HIGH***	LOW TO HIGH	LOW TO MEDIUM	MEDIUM
FORCE	HIGH ~100 kgm FORCE	MEDIUM ~1 kgm FORCE	SMALL	SMALL	HIGH
HYSTERISIS	TAILORABLE BY COMPOSITION	SMALL	LARGE	SMALL TO MEDIUM	LARGE
AGING	COMPOSITION DEPENDENT	VERY SMALL	LARGE	LARGE	SMALL
TEMPERATURE RANGE OF OPERATION	–196°C → 300°C WIDE	–196°C → 100°C WIDE	–50°C → 150°C MEDIUM	–10°C → 80°C LIMITED	–273°C → 100°C WIDE
RESPONSE SPEED	μsec-msec	msec -sec	μsec-msec	μsec-msec	μsec-msec
ACTIVATION MODE	BOTH OPTICAL AND ELECTRICAL	THERMAL AND ELECTRICAL	ELECTRICAL	ELECTRICAL	MAGNETIC
POWER REQUIREMENT	LOW	LOW to MEDIUM	MEDIUM	LOW TO MEDIUM	HIGH
RADIATION HARDNESS	YES	YES	TBD	TBD	YES
CYCLABILITY	EXCELLENT	GOOD	FAIR	FAIR-FOOR	GOOD
PROSPECT OF MINIATURIZATION	GOOD	GOOD	GOOD	GOOD	FAIR

and illustrates how piezoceramics are one of the leading candidate, **especially when dimensions shrink and approach those of thin films,** where properties are tailorable by fine composition control. Thin film growth techniques through their close control on composition allow a much finer control of hysterisis and aging properties. In particular, the lower holding power requirement by piezoceramics makes them attractive over magnetic actuators which suffer from the need for significant heat dissipation. With size reduction, the energy absorbed by piezoceramics could be up to two orders of magnitude higher[18] compared to electrostatic and magnetic actuators. This higher density is attributed to the higher dielectric constant of the piezoceramics and the increasing breakdown field with reducing thickness[18]. Furthermore, piezoceramics offer the potential of solar driven, tetherless mechanisms since they can be actuated[18, 20, 52-56] directly by optical illumination (350nm to 450 nm). Piezoceramic actuation is potentially robust, amenable to low temperature operation, and intrinsically radiation-resistant. In addition, their ability to be batch-produced by thin film manufacturing techniques on large substrate areas offers convenience and cost effectiveness. Shape memory alloys offer many of these benefits too, except that they are relatively slow as the phenomenon is thermal in nature. However, their technology readiness for flexible actuator usage is at a much higher level.

Innovations[48] based on advanced composite materials/flexible substrate-based flexible actuators, employing innovative amplification techniques to provide the desired combination of *high force and displacement characteristics*

Table 4: Challenges, Pay-off, and Key features of Innovation Options

OPTIONS	FABRICATION CHALLENGE	PAY-OFF	FEATURES ENHANCED
I	LOW	MEDIUM	HIGH FORCE, MEDIUM DEFLECTION WIDE TEMP RANGE OPERATION MEDIUM SPEED, ELECTRICALLY OPERATED
II	MEDIUM	MEDIUM	MEDIUM FORCE, HIGH DEFLECTION SCALEABLE, MEMS WIDE TEMP RANGE OPERATION MEDIUM SPEED, ELECTRICALLY OPERATED
III	HIGH	HIGH	HIGH FORCE& DEFLECTION COMBINATION, SCALEABLE, MEMS WIDE TEMP RANGE OPERATION HIGH SPEED, ELECTRICALLY & OPTICALLY OPERABLE

are being worked on to realize the building blocks of this new paradigm in mobility. The innovation options are summarized in Table 4.

IIIC. 3. Why Bio-morphic Controls Implemented on a Neural Network Chip?

The flexible actuators proposed are non-linear systems that are controlled most effectively by control mechanisms that allow adaptation of control sequence to determine its parameters while acting on the target environment as required. The recent emergence of neuro-reflexive control, a powerful paradigm that offers for the first time real-time adaptivity and learning ability with inherent fault tolerance, would make it possible to capture these attributes in an on-board, compact control hardware, not possible with conventional technology suite. Combining the flexible actuators and biomorphic controls would therefore offer for the first time a new direction in advanced mobility with new capabilities of adapting to terrain, enhanced spatial access owing to flexibility, scalability, and ease of multiplicity due batch process amenable fabrication.

The Control Algorithm applied to the explorer design(s) is expected to result in a complex multivariable transformation(s) matrix that would map the input (signals from a variety of strategically positioned sensors) on to the corresponding responses (actuator triggers for mobility, gait, and explorer configurations). Example inputs and outputs are:

Inputs:
- signals from a body-mounted 'level' sensor,
- 6 (or more) leg-mounted and 2 (or more) feeler/antennae-mounted strain gauge sensors,
- 2 (or more) feeler/antennae-mounted chemical (moisture) sensors,
- several body/leg/feeler-mounted proximity sensors, etc.

outputs:
- simple trigger for individual leg/limb actuation and or antenna articulation,
- a full repeated sequence of all the legs in a predetermined pattern to move with a specific gait,
- gradual or sudden change of the sequence or pattern to change the gait/speed,
- a turn or a change in the heading, reverse motion,
- release of broader foot-print,
- on/off of a one or more specific leg(s) to execute a specific motion sequence, etc.

For an autonomous and real-time mobility control, the transformation/mapping must reside on board with minimal "load" on the explorer's mass/volume/power resources. Therefore, this development will use a JPL-pioneered, low-power, custom-VLSI, fully parallel (and therefore high speed) artificial neural network (ANN) building block chip (described below) which could be trained/programmed to capture the exact mapping function in it. Furthermore, the ANN architecture would not only be able to generalize (interpolate as well as extrapolate to some extent) from its programmed routines, but in the future could also be set to learn from the following:
- experiences gathered from the explorer's motion,
- information collected about the environment,
- as well as the nuances of the explorer body, leg behavior etc.

The proposed activity will draw heavily on **JPL's** extensive experience in custom-VLSI low-power implementations of application-specific concurrent processors, developed over the last ten years with primary funding support from the Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA). JPL has already **demonstrated**[9] low-power neural network chips in custom-Complementary Metal Oxide Semiconductor (CMOS) state-of-the-art VLSI architectures implemented as neuroprocessing “building block” chips. JPL has developed a variety of devices, such as wide range variable gain, linear and sigmoidal neurons, **7-** to 1 l-bit resolution synapses, high speed winner- and loser-take-all circuits, multiplexers, encoders, decoders, buffers, programmable switches, and stable high speed digital-to-analog (DAC) converters.

M.D. DETAILED TECHNICAL APPROACH:

In accordance with the overall focus of this effort we have selected truly simple but elegant actuation mechanisms to interface with the adaptive controls.

IIID. 1. Mobility

Overview of Six-Legged Explorer

The explorer shown in figure 3 is designed for multi- terrain traverse. It utilizes six legs, each of which have two rotational degrees of freedom at a shoulder ball-pivot. The rotations at the shoulder result in net translation of the feet. In this way, the robot can be made to both step forward and up. To augment the capabilities of the explorer, the mobility system can be reconfigurable, either by changing its footprint or by changing the overall length of the leg, or both. The actuation is based on sets of SMA wires and cantilever springs. An individual set consists of a wire and a spring attached to the end of the leg lever arm in linear apposition. Two orthogonal sets comprise one actuation cell, capable of moving a leg with two degrees of freedom. In the case of a vertical set, the spring is designed to support the weight of the explorer, while the SMA need only stretch the spring. This reduces the necessary maximum force rating of the SMA. A lower maximum force rating implies a smaller diameter wire, which requires less power and has a faster cycle time. Preliminary estimates indicate that a 37 □m SMA wire would suffice for the force and power required to obtain this mechanism. A refinement of the actuation would place several wires in series, for each set, this arrangement would allow for variable step size (steering).

Reconfigurable Foot Overview

The reconfigurable foot (figure 4A and 4B) is intended to provide a good grip on a range of substrates from hard and rocky to soft and sandy respectively. This effect is achieved through a variable footprint design. For a hard matrix, the scissor-like foot is retracted into the leg via the contraction of a SMA wire. This presents a footprint that is primarily composed of the leading edges of the foot pads. For a soft matrix, the SMA is relaxed, and the torsional

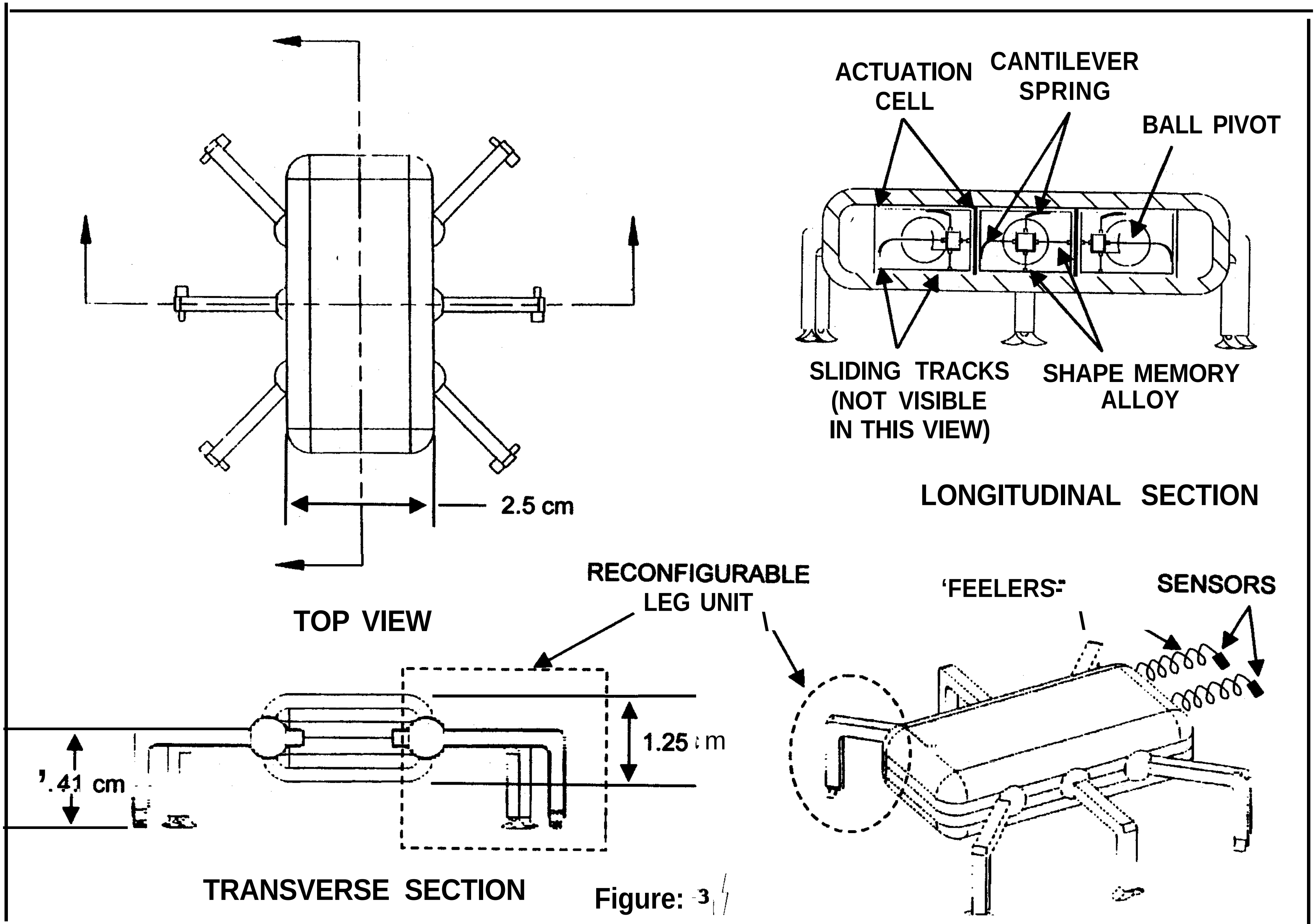
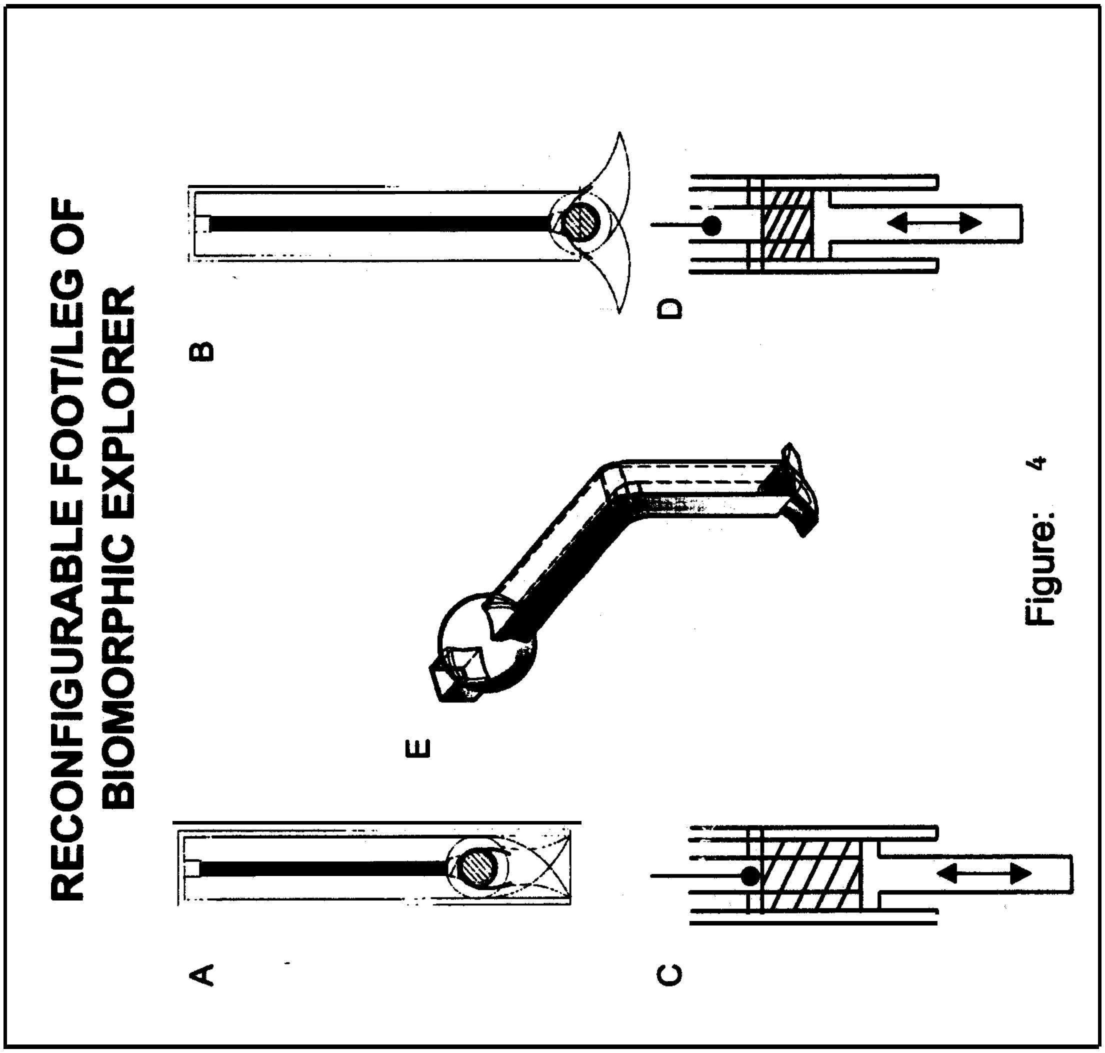

ACTUATION CELL
CANTILEVER SPRING
BALL PIVOT
SLIDING TRACKS (NOT VISIBLE IN THIS VIEW)
SHAPE MEMORY ALLOY
LONGITUDINAL SECTION
2.5 cm
TOP VIEW
RECONFIGURABLE LEG UNIT
'FEELERS'
SENSORS
1.25 m
.41 cm
TRANSVERSE SECTION

Figure: 3


RECONFIGURABLE FOOT/LEG OF
BIOMORPHIC EXPLORER
A
B
C
D
E
Figure: 4

spring wrapped around the foot axle pulls the foot out the leg housing and spreads the foot pads to their greatest extent. The footprint in this case is the full flats of the foot pads.

Reconfigurable Leg Overview

The reconfigurable leg (figure 4C and 4D) would be a way to have a robot that was capable of relatively high giound force as well as relatively high ground speed, though not at the same time. In essence, it simply is a telescopic leg, the extension and retraction of which is governed by an appositional set of SMA wire and tension spring. Whether the SMA actuates the extension or retraction is arbitrary. If the extension of the leg is perpendicular to the direction of the leg travel (and net actuation force), the load on the actuator will go down with the percentage decrease in effective leg length, and the step size will increase with the percentage increase in effective leg length. In other words, the load on the actuators can be decreased in situations such as going up hill and lifting the robot over obstacles by shortening the leg, and the speed can be increased over flat ground by lengthening the legs.

Overview of a Proposed Burrowing Worm-Robot:

Taking inspiration from the burrowing techniques of *Amphisbaenia* (as presented by Gans), a proposed design for a subterranean worm-robot has been created. The *Amphisbaenia,* a generally leg-less order of reptiles, create tunnels by forcing themselves through the soil. More specifically, they impact the head of the tunnel with their own heads, then compact the soil into the walls of the tunnel. Different species accomplish these actions in different but similar ways. In general, annular rings along the body are expanded against the tunnel's wall, anchoring the animal. A rectilinear motion is then created, culminating in the head striking (relatively speaking) the head of the tunnel. Once the snout is wedged within the soil, the head is moved back and forth or up and down (keel- or spade-headed species, respectively). This motion compacts the soil in the walls and opens the tunnel so that the animal can move forward. The process is then repeated The *Arnphisbaenia* are a successful order of reptiles that move through the soil in a manner and with an efficiency that conventional mechanical systems cannot. If a rover were created that could mimic the majority of their movement modes, that rover should be able to burrow with an efficiency approaching that of the reptiles. The proposed design will be a first step in that direction.

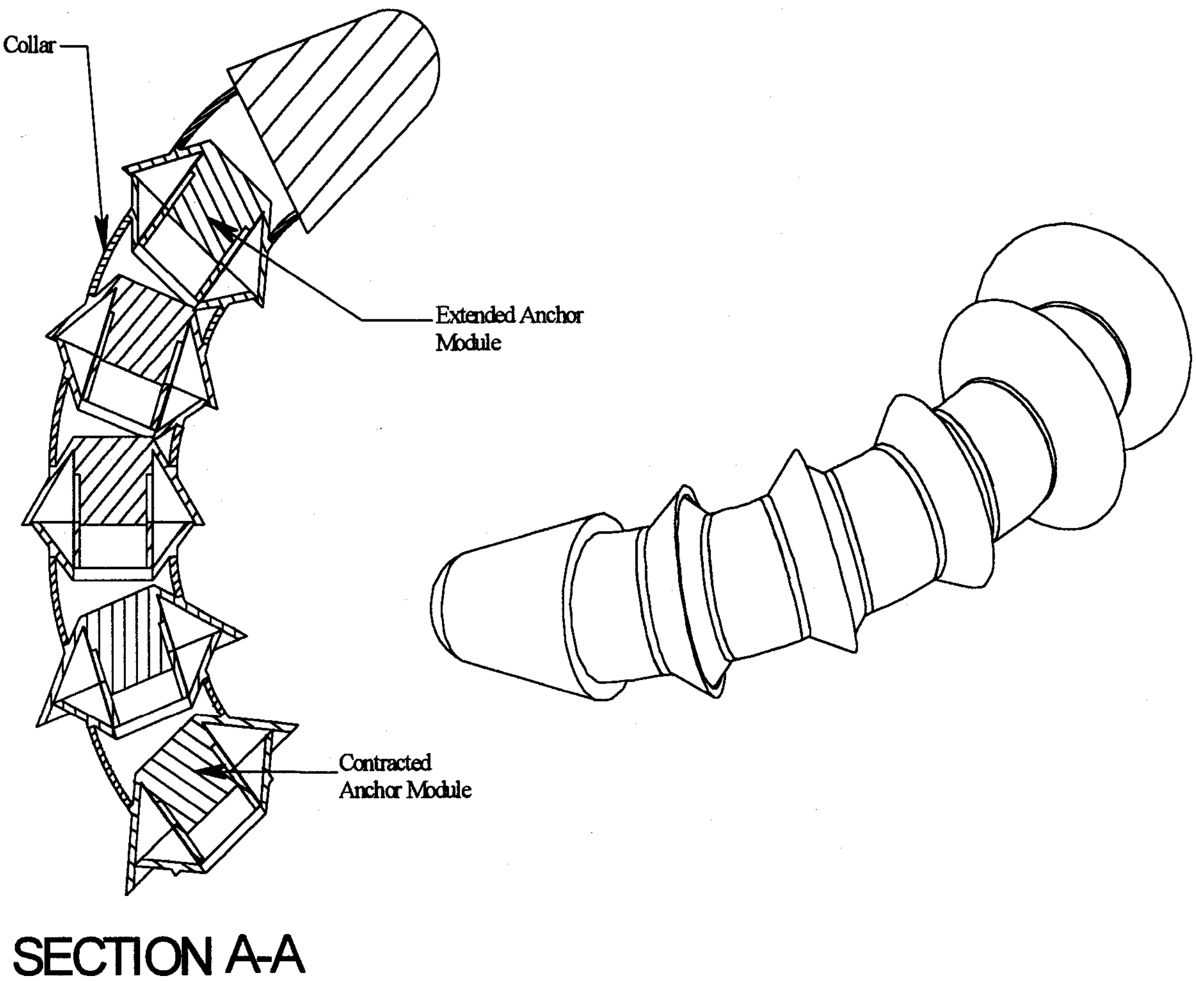


Figure 5
Explorer Mobility:

To emulate the behavior of these reptiles requires a mobility system capable of two distinct motions: anchored rectilinear motion and transverse movement of the head and body. The accompanying schematic (figure 5) shows a design composed of a series of modules capable of creating these motions.

- The anchored rectilinear motion is provided by the modules that look like two cones placed base to base. Within these cones is a piston-like assembly, actuated by parallel sets of spring-opposed SMA wires (shown in red). When the piston is actuated, the outer cone is expanded, providing an anchor in the tunnel walls. Meanwhile, the module's length is decreased. The sketch shows the two rear modules in anchor mode and the three forward modules in extended mode. If the body is anchored by other modules, the release of a particular piston results in the net forward motion of the corresponding module.
- Connecting the anchor modules are collars of a flexible matrix with embedded SMA wires. These wires are placed longitudinally about the

circumference of the collar. As the wires are differentially energized (i.e., just those of the bottom quarter), the collar will have a tendency to bend toward those wires. In this way all or parts of the body can be arched.

Special Issues in the Implementation of this Mobility Svstem

Gans' work provides something of a blueprint for mobility of a system as has been described. In general, the movement will proceed as described above with the gradual lengthening and widening of a tunnel. A troublesome case, however, is the initial entry into the soil. The simplest solution is to burrow into the side of a hill. In this case, the method is the same as for normal burrowing; except the anchor modules can only use the surface soil for resistance. It may be necessary to first dig a starter hole by moving the head into a position normal to the surface by arching the appropriate collars, then pivoting the head about the point of the snout. This movement will eventually displace enough soil that a more normal mode of movement may be used.

Design Refinements

- To decrease frictional losses, all cone surfaces that are directly loaded by the soil should be covered by some Teflon-like coating.
- Depending on the soil conditions and mobility requirements, different head designs could be used. (I.e., a spade-head might be more useful for deep-burrowing rovers as opposed to a keel-head, which might be more useful for in-the-plane steering.

Aqua- Worm

A possible variation of the peristaltic worm design would be a explorer capable of over land and through water. Since the general form of locomotion of the peristaltic worm treats soil as a highly viscous fluid, the design could be refined to allow motion through less viscous fluids such as water. The primary difference would be the inclusion of louvers in the anchor plates. These louvers would act as one-way valves though which water could pass as a module moved forward, but which would resist backward motion as the module came into the anchored configuration. These louvers could be either passive, using the force of the water to close them, or active. If the water body is much more than a puddle, some type of buoyancy system would have to be developed, the simplest of which would have the explorer be neutrally buoyant at some predetermined depth.

IIID. 2. Logical Architecture for Bio-morphic Controls:

In biological systems, the control of periodic limb motion sequences are generally delegated to a lower level controller (e.g. spinal cord in humans) than the main CPU (e.g. the brain). This relieves the brain resources to attend to the higher level cognitive functions including sensory information processing (e.g. vision, hearing, etc.). This arrangement does not rule out a higher level command from the brain to the spinal cord to modulate/change the ongoing periodic motion whenever necessary based on sensory input received and processed. For example, decision to turn or run in a specific direction rather than walk in the sight of a prey/predator is executed by a neuro-reflexive loop originating within the spinal cord.

Similarly, control for bio-morphic explorers could be considered at several levels. At the lowest level is the motion control, including the basic locomotion and articulation. At a higher level, primitive actions such as "move forward" and "turn" are coordinated with sensory input and integrated using an action selection mechanism into more complex behaviors such as "wander around searching for samples while avoiding obstacles". An even higher level of control is the coordination of groups of bio-morphic explorers to achieve mission-level tasks.

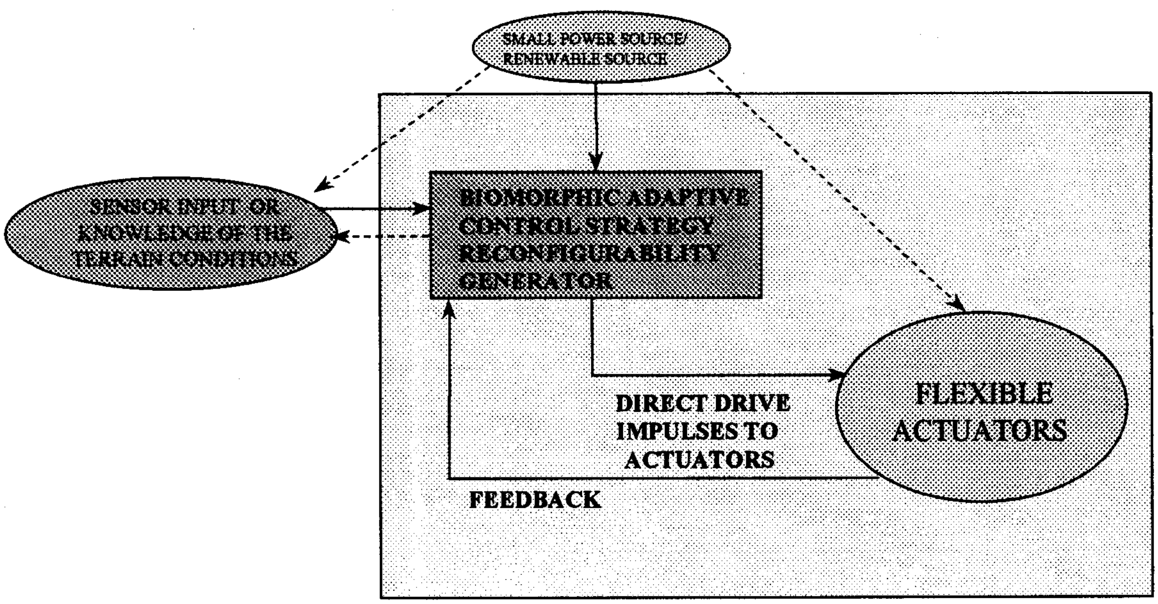


Figure 6: Implementation schematic of bio-morphic explorer

In this effort, our initial focus will be on motion control, which will serve as a proof-of-concept demonstration and a foundation for higher level controls. As illustrated in Figure 6, the knowledge of terrain conditions and real-time sensor input about environment will govern the optimization of coding and representation of the control algorithm. The controller can hence generate outputs that provide actuator shape control (i.e., reconfiguration) as well as control of mobility attributes to adapt to environmental conditions.

Motion Control

The use of flexible actuators for mobility poses a control problem: the coordination of the movement of actuators to achieve desired motions such as locomotion. The desirable characteristics of a control mechanism for bio-morphic explorers include:

1) *Learning:* automatic generation of efficient motions to achieve-mobility
2) *Adaptation:* ability to autonomously match terrain and environmental conditions
3) *Fault tolerance:* ability to generate new motions to compensate for possible damage to part of the robot
4) ***Composability***: ability to smoothly integrate various primitive motions into complex motions and activities
5) *Generality:* ideally, the mechanism should be general enough so that the control methodology can be applied to a large class of bio-morphic robots.

Recently, there have been significant advances in the real-time, adaptive control of legged robots for mobility. Typically, the control mechanisms used are based on biological principles: a neurally inspired controller (an artificial neural network) is generated using a reinforcement learning.

*1110.3. **Chip** controller* Hardware:

A robust and versatile neuroprocessing architecture, shown in Figure 7 has been developed with a number of unique design attributes. This chip (NN 64) is essentially a high speed, analog vector matrix multiplier that is capable of receiving 64 simultaneous input signals (say, from sensors), and after modulating those with the predetermined "synaptic,, weights (initially generated off-line by the BSR algorithm), delivering outputs to the response generating circuitry. It also offers a layer of non-linear (sigmoid) neurons on the same chip, to capture nonlinearities in the transformations.

As shown in figure 9, the same chip could also be configured in the most powerful multilayer feedforward ANN architecture as illustrated in the figure. The number of inputs would be primariliy dictated by the number of sensor inputs. Further, the number of neural layers required and the overall network architecture will of course depend on the BSR algorithm. The final output for generating the trigger responses would be obtained from up to 64 output neurons.

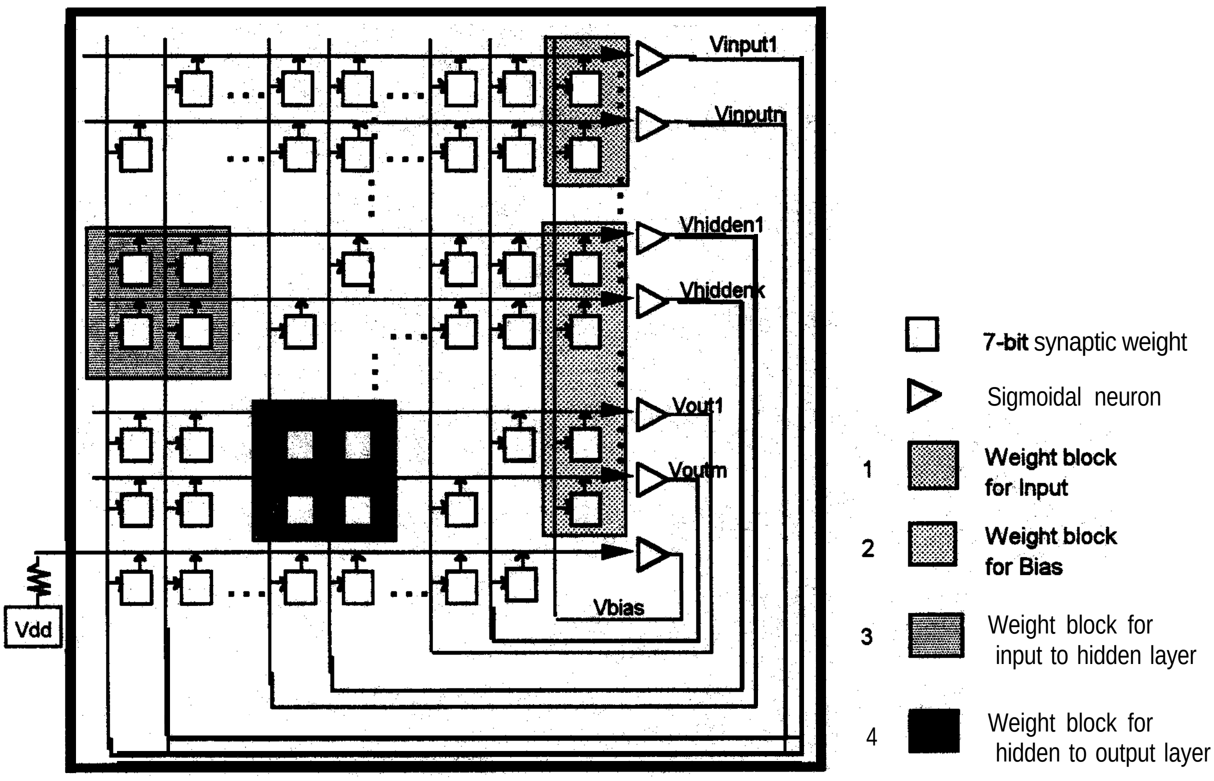


Figure 7. A block diagram of a Programmable Neuroprocessing architecture. The architecture is versatile and software programmable with various learning schemes for capturing complex, ill-defined mapping in multivariable functions.